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Substation Grounding

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11.1 Reasons for Substation Grounding System

The substation grounding system is an essential part of the overall electrical system. The proper grounding of a substation is important for the following two reasons:

1. It provides a means of dissipating electric current into the earth without exceeding the operating limits of the equipment
2. It provides a safe environment to protect personnel in the vicinity of grounded facilities from the dangers of electric shock under fault conditions

The grounding system includes all of the interconnected grounding facilities in the substation area, including the ground grid, overhead ground wires, neutral conductors, underground cables, foundations, deep well, etc. The ground grid consists of horizontal interconnected bare conductors (mat) and ground rods. The design of the ground grid to control voltage levels to safe values should consider the total grounding system to provide a safe system at an economical cost.

The following information is mainly concerned with personnel safety. The information regarding the grounding system resistance, grid current, and ground potential rise can also be used to determine if the operating limits of the equipment will be exceeded.

Safe grounding requires the interaction of two grounding systems:

1. The intentional ground, consisting of grounding systems buried at some depth below the earth's surface
2. The accidental ground, temporarily established by a person exposed to a potential gradient in the vicinity of a grounded facility

It is often assumed that any grounded object can be safely touched. A low substation ground resistance is not, in itself, a guarantee of safety. There is no simple relation between the resistance of the grounding system as a whole and the maximum shock current to which a person might be exposed. A substation with relatively low ground resistance might be dangerous, while another substation with very high ground resistance might be safe or could be made safe by careful design.

There are many parameters that have an effect on the voltages in and around the substation area. Since voltages are site-dependent, it is impossible to design one grounding system that is acceptable for all locations. The grid current, fault duration, soil resistivity, surface material, and the size and shape of the grid all have a substantial effect on the voltages in and around the substation area. If the geometry, location of ground electrodes, local soil characteristics, and other factors contribute to an excessive potential gradient at the earth surface, the grounding system may be inadequate from a safety aspect despite its capacity to carry the fault current in magnitudes and durations permitted by protective relays.

During typical ground fault conditions, unless proper precautions are taken in design, the maximum potential gradients along the earth surface may be of sufficient magnitude to endanger a person in the area. Moreover, hazardous voltages may develop between grounded structures or equipment frames and the nearby earth.

The circumstances that make human electric shock accidents possible are:

- Relatively high fault current to ground in relation to the area of the grounding system and its resistance to remote earth
- Soil resistivity and distribution of ground currents such that high potential gradients may occur at points at the earth surface
- Presence of a person at such a point, time, and position that the body is bridging two points of high potential difference
- Absence of sufficient contact resistance or other series resistance to limit current through the body to a safe value under the above circumstances
- Duration of the fault and body contact and, hence, of the flow of current through a human body for a sufficient time to cause harm at the given current intensity

The relative infrequency of accidents is due largely to the low probability of coincidence of the above unfavorable conditions.

To provide a safe condition for personnel within and around the substation area, the grounding system design limits the potential difference a person can come in contact with to safe levels. IEEE Std. 80, IEEE Guide for Safety in AC Substation Grounding [1], provides general information about substation grounding and the specific design equations necessary to design a safe substation grounding system. The following discussion is a brief description of the information presented in IEEE Std. 80.

The guide's design is based on the permissible body current when a person becomes part of an accidental ground circuit. Permissible body current will not cause ventricular fibrillation, i.e., stoppage of the heart. The design methodology limits the voltages that produce the permissible body current to a safe level.

11.2 Accidental Ground Circuit

11.2.1 Conditions

There are two conditions that a person within or around the substation can experience that can cause them to become part of the ground circuit. One of these conditions, touch voltage, is illustrated in Figure 11.1 and Figure 11.2. The other condition, step voltage, is illustrated in Figure 11.3 and Figure 11.4. Figure 11.1 shows the fault current being discharged to the earth by the substation grounding system and a person touching a grounded metallic structure, H. Figure 11.2 shows the Thevenin equivalent for the person's feet in parallel, Z_{th} , in series with the body resistance, R_b . V_{th} is the voltage between terminal H and F when the person is not present. I_b is the body current. When Z_{th} is equal to the resistance of two feet in parallel, the touch voltage is

$$E_{touch} = I_b (R_b + Z_{th}) \quad (11.1)$$

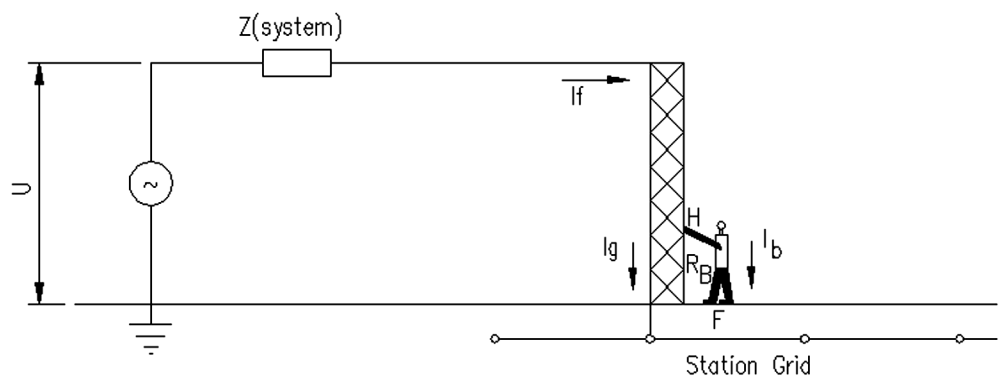


FIGURE 11.1 Exposure to touch voltage.

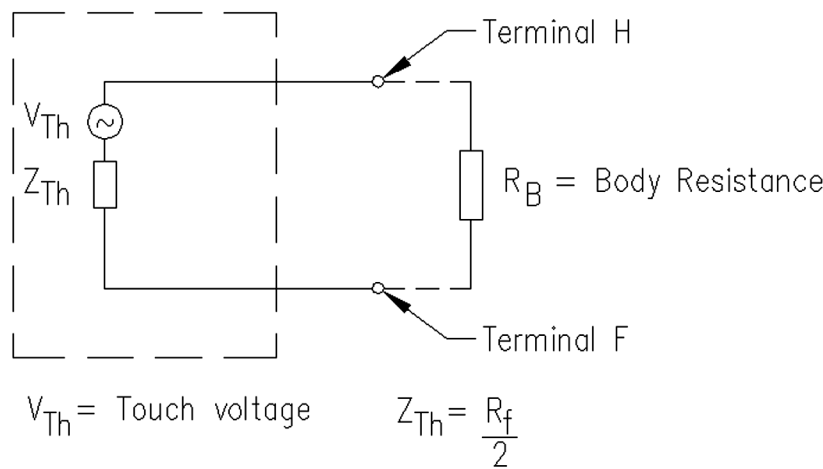


FIGURE 11.2 Touch-voltage circuit.

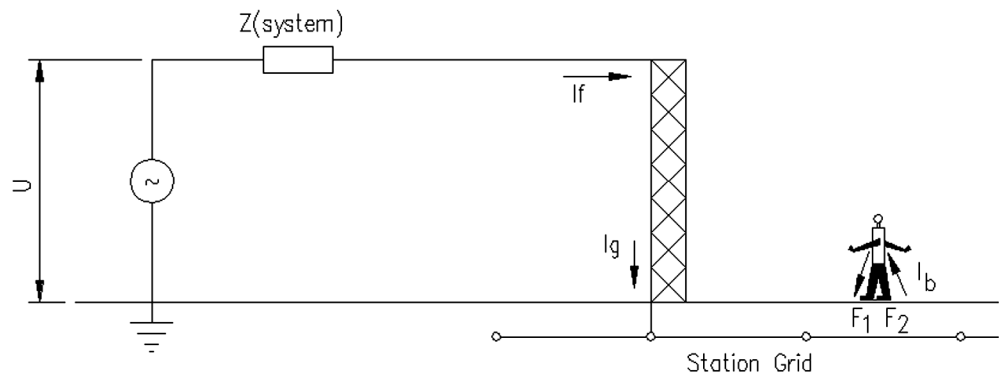


FIGURE 11.3 Exposure to step voltage.

Figure 11.3 and Figure 11.4 show the conditions for step voltage. Z_{th} is the Thevenin equivalent impedance for the person's feet in series and in series with the body. Based on the Thevenin equivalent impedance, the step voltage is

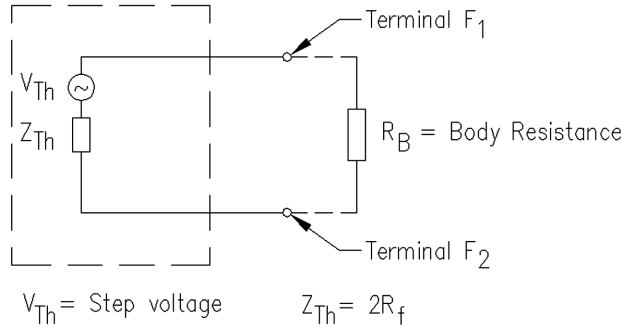


FIGURE 11.4 Step-voltage circuit.

$$E_{step} = I_b (R_B + Z_{th}) \quad (11.2)$$

The resistance of the foot in ohms is represented by a metal circular plate of radius b in meters on the surface of homogeneous earth of resistivity ρ ($\Omega\text{-m}$) and is equal to:

$$R_f = \frac{\rho}{4b} \quad (11.3)$$

Assuming $b = 0.08$

$$R_f = 3\rho \quad (11.4)$$

The Thevenin equivalent impedance for 2 feet in parallel in the touch voltage, E_{touch} , equation is

$$Z_{Th} = \frac{R_f}{2} = 1.5\rho \quad (11.5)$$

The Thevenin equivalent impedance for 2 feet in series in the step voltage, E_{step} , equation is

$$Z_{Th} = 2R_f = 6\rho \quad (11.6)$$

The above equations assume uniform soil resistivity. In a substation, a thin layer of high-resistivity material is often spread over the earth surface to introduce a high-resistance contact between the soil and the feet, reducing the body current. The surface-layer derating factor, C_s , increases the foot resistance and depends on the relative values of the resistivity of the soil, the surface material, and the thickness of the surface material.

The following equations give the ground resistance of the foot on the surface material.

$$R_f = \left[\frac{\rho_s}{4b} \right] C_s \quad (11.7)$$

$$C_s = 1 + \frac{16b}{\rho_s} \sum_{n=1}^{\infty} K^n R_{m(2nh_s)} \quad (11.8)$$

$$K = \frac{\rho - \rho_s}{\rho + \rho_s} \quad (11.9)$$

where

- C_s is the surface layer derating factor
- K is the reflection factor between different material resistivities
- ρ_s is the surface material resistivity in $\Omega\text{-m}$

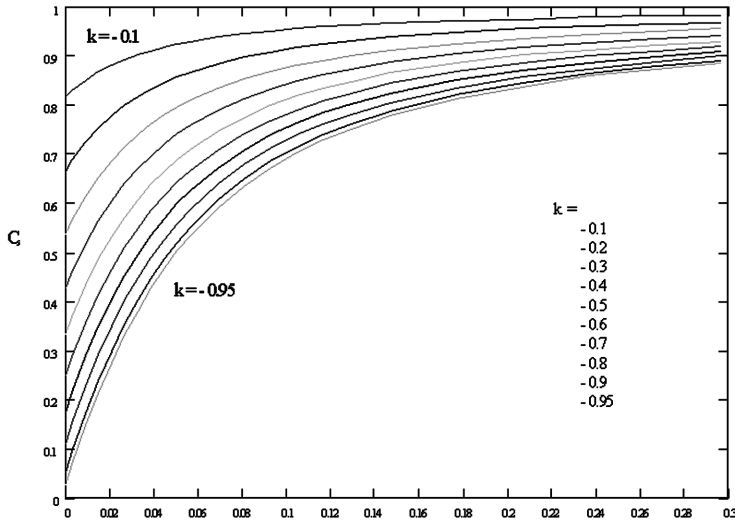


FIGURE 11.5 C_s versus h_s .

ρ is the resistivity of the earth beneath the surface material in $\Omega\text{-m}$

h_s is the thickness of the surface material in m

b is the radius of the circular metallic disc representing the foot in m

$R_m(2nh_s)$ is the mutual ground resistance between the two similar, parallel, coaxial plates, separated by a distance $(2nh_s)$, in an infinite medium of resistivity ρ_s in $\Omega\text{-m}$

A series of C_s curves has been developed based on Equation 11.8 and $b = 0.08$ m, and is shown in Figure 11.5.

The following empirical equation by Sverak [2], and later modified, gives the value of C_s . The values of C_s obtained using Equation 11.10 are within 5% of the values obtained with the analytical method [3].

$$C_s = 1 - \frac{0.09 \left(1 - \frac{\rho}{\rho_s} \right)}{2h_s + 0.09} \quad (11.10)$$

11.2.2 Permissible Body Current Limits

The duration, magnitude, and frequency of the current affect the human body as the current passes through it. The most dangerous impact on the body is a heart condition known as ventricular fibrillation, a stoppage of the heart resulting in immediate loss of blood circulation. Humans are very susceptible to the effects of electric currents at 50 and 60 Hz. The most common physiological effects as the current increases are perception, muscular contraction, unconsciousness, fibrillation, respiratory nerve blockage, and burning [4]. The threshold of perception, the detection of a slight tingling sensation, is generally recognized as 1 mA. The let-go current, the ability to control the muscles and release the source of current, is recognized as between 1 and 6 mA. The loss of muscular control may be caused by 9 to 25 mA, making it impossible to release the source of current. At slightly higher currents, breathing may become very difficult, caused by the muscular contractions of the chest muscles. Although very painful, these levels of current do not cause permanent damage to the body. In a range of 60 to 100 mA, ventricular fibrillation occurs. Ventricular fibrillation can be a fatal electric shock. The only way to restore the normal heartbeat is through another controlled electric shock, called defibrillation. Larger currents will inflict nerve damage and burning, causing other life-threatening conditions.

The substation grounding system design should limit the electric current flow through the body to a value below the fibrillation current. Dalziel [5] published a paper introducing an equation relating the

flow of current through the body for a specific time that statistically 99.5% of the population could survive before the onset of fibrillation. This equation determines the allowable body current.

$$I_B = \frac{k}{\sqrt{t_s}} \quad (11.11)$$

where

I_B = rms magnitude of the current through the body, A

t_s = duration of the current exposure, sec

$k = \sqrt{S_B}$

S_B = empirical constant related to the electric shock energy tolerated by a certain percent of a given population

Dalziel found the value of $k = 0.116$ for persons weighing approximately 50 kg (110 lb) or $k = 0.157$ for a body weight of 70 kg (154 lb) [6]. Based on a 50-kg weight, the tolerable body current is

$$I_B = \frac{0.116}{\sqrt{t_s}} \quad (11.12)$$

The equation is based on tests limited to values of time in the range of 0.03 to 3.0 sec. It is not valid for other values of time. Other researchers have suggested other limits [7]. Their results have been similar to Dalziel's for the range of 0.03 to 3.0 sec.

11.2.3 Importance of High-Speed Fault Clearing

Considering the significance of fault duration both in terms of Equation 11.11 and implicitly as an accident-exposure factor, high-speed clearing of ground faults is advantageous for two reasons:

1. The probability of exposure to electric shock is greatly reduced by fast fault clearing time, in contrast to situations in which fault currents could persist for several minutes or possibly hours.
2. Both tests and experience show that the chance of severe injury or death is greatly reduced if the duration of a current flow through the body is very brief.

The allowed current value may therefore be based on the clearing time of primary protective devices, or that of the backup protection. A good case could be made for using the primary clearing time because of the low combined probability that relay malfunctions will coincide with all other adverse factors necessary for an accident. It is more conservative to choose the backup relay clearing times in Equation 11.11, because it assures a greater safety margin.

An additional incentive to use switching times less than 0.5 sec results from the research done by Biegelmeier and Lee [7]. Their research provides evidence that a human heart becomes increasingly susceptible to ventricular fibrillation when the time of exposure to current is approaching the heartbeat period, but that the danger is much smaller if the time of exposure to current is in the region of 0.06 to 0.3 sec.

In reality, high ground gradients from faults are usually infrequent, and shocks from this cause are even more uncommon. Furthermore, both events are often of very short duration. Thus, it would not be practical to design against shocks that are merely painful and cause no serious injury, i.e., for currents below the fibrillation threshold.

11.2.4 Tolerable Voltages

Figure 11.6 and Figure 11.7 show the five voltages a person can be exposed to in a substation. The following definitions describe the voltages.

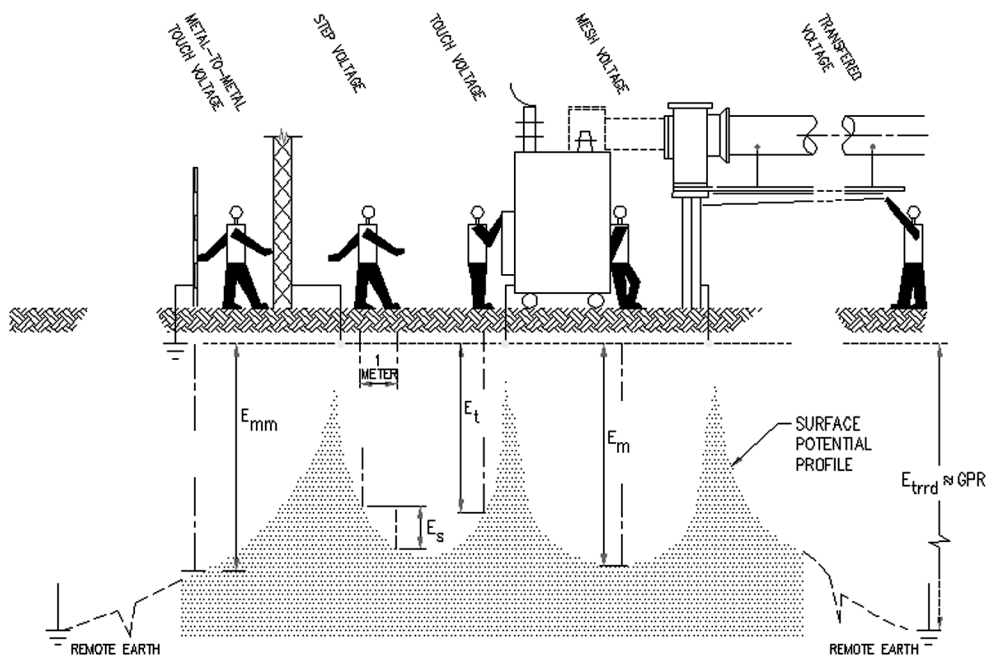


FIGURE 11.6 Basic shock situations.

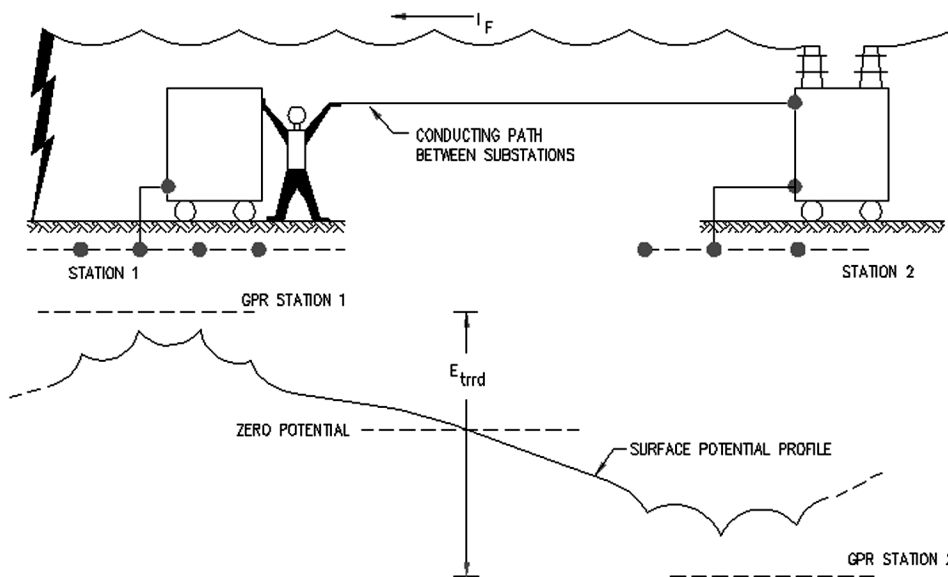


FIGURE 11.7 Typical situation of external transferred potential.

Ground potential rise (GPR): The maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. GPR is the product of the magnitude of the grid current, the portion of the fault current conducted to earth by the grounding system, and the ground grid resistance.

Mesh voltage: The maximum touch voltage within a mesh of a ground grid.

Metal-to-metal touch voltage: The difference in potential between metallic objects or structures within the substation site that can be bridged by direct hand-to-hand or hand-to-feet contact. Note: The metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid is assumed to be negligible in conventional substations. However, the metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid and metallic objects inside the substation site but not bonded to the ground grid, such as an isolated fence, may be substantial. In the case of gas-insulated substations, the metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid may be substantial because of internal faults or induced currents in the enclosures.

Step voltage: The difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any other grounded object.

Touch voltage: The potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure.

Transferred voltage: A special case of the touch voltage where a voltage is transferred into or out of the substation, from or to a remote point external to the substation site. The maximum voltage of any accidental circuit must not exceed the limit that would produce a current flow through the body that could cause fibrillation.

Assuming the more conservative body weight of 50 kg to determine the permissible body current and a body resistance of 1000 Ω , the tolerable touch voltage is

$$E_{touch50} = \left(1000 + 1.5C_s \cdot \rho_s\right) \frac{0.116}{\sqrt{t_s}} \quad (11.13)$$

and the tolerable step voltage is

$$E_{step50} = \left(1000 + 6C_s \cdot \rho_s\right) \frac{0.116}{\sqrt{t_s}} \quad (11.14)$$

where

E_{step} = step voltage, V

E_{touch} = touch voltage, V

C_s = determined from [Figure 11.5](#) or [Equation 11.10](#)

ρ_s = resistivity of the surface material, Ω -m

t_s = duration of shock current, sec

Since the only resistance for the metal-to-metal touch voltage is the body resistance, the voltage limit is

$$E_{mm-touch50} = \frac{116}{\sqrt{t_s}} \quad (11.15)$$

The shock duration is usually assumed to be equal to the fault duration. If reclosing of a circuit is planned, the fault duration time should be the sum of the individual faults and used as the shock duration time t_s .

11.3 Design Criteria

The design criteria for a substation grounding system are to limit the actual step and mesh voltages to levels below the tolerable step and touch voltages as determined by Equations 11.13 and 11.14. The worst-case touch voltage, as shown in [Figure 11.6](#), is the mesh voltage.

11.3.1 Actual Touch and Step Voltages

The following discusses the methodology to determine the actual touch and step voltages.

11.3.1.1 Mesh Voltage (E_m)

The actual mesh voltage, E_m (maximum touch voltage), is the product of the soil resistivity, ρ ; the geometrical factor based on the configuration of the grid, K_m ; a correction factor, K_i , that accounts for some of the error introduced by the assumptions made in deriving K_m ; and the average current per unit of effective buried length of the conductor that makes up the grounding system (I_G/L_M).

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M} \quad (11.16)$$

The geometrical factor K_m [2] is as follows:

$$K_m = \frac{1}{2 \cdot \pi} \cdot \left[\ln \left[\frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h)^2}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d} \right] + \frac{K_{ii}}{K_h} \cdot \ln \left[\frac{8}{\pi(2 \cdot n - 1)} \right] \right] \quad (11.17)$$

For grids with ground rods along the perimeter, or for grids with ground rods in the grid corners, as well as both along the perimeter and throughout the grid area, $K_{ii} = 1$. For grids with no ground rods or grids with only a few ground rods, none located in the corners or on the perimeter,

$$K_{ii} = \frac{1}{(2 \cdot n)^{\frac{2}{n}}} \quad (11.18)$$

$$K_h = \sqrt{1 + \frac{h}{h_o}}, \quad h_o = 1 \text{ m (grid reference depth)} \quad (11.19)$$

Using four grid-shape components [8], the effective number of parallel conductors in a given grid, n , can be made applicable to both rectangular and irregularly shaped grids that represent the number of parallel conductors of an equivalent rectangular grid:

$$n = n_a \cdot n_b \cdot n_c \cdot n_d \quad (11.20)$$

where

$$n_a = \frac{2 \cdot L_c}{L_p} \quad (11.21)$$

$n_b = 1$ for square grids

$n_c = 1$ for square and rectangular grids

$n_d = 1$ for square, rectangular, and L-shaped grids

Otherwise,

$$n_b = \sqrt{\frac{L_p}{4 \cdot \sqrt{A}}} \quad (11.22)$$

$$n_c = \left[\frac{L_x \cdot L_y}{A} \right]^{\frac{0.7 \cdot A}{L_x \cdot L_y}} \quad (11.23)$$

$$n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}} \quad (11.24)$$

where

L_c = total length of the conductor in the horizontal grid, m

L_p = peripheral length of the grid, m

A = area of the grid, m²

L_x = maximum length of the grid in the x direction, m

L_y = maximum length of the grid in the y direction, m

D_m = maximum distance between any two points on the grid, m

D = spacing between parallel conductors, m

h = depth of the ground grid conductors, m

d = diameter of the grid conductor, m

I_G = maximum grid current, A

The irregularity factor, K_i , used in conjunction with the above-defined n , is

$$K_i = 0.644 + 0.148 \cdot n \quad (11.25)$$

For grids with no ground rods, or grids with only a few ground rods scattered throughout the grid, but none located in the corners or along the perimeter of the grid, the effective buried length, L_M , is

$$L_M = L_C + L_R \quad (11.26)$$

where L_R = total length of all ground rods, in meters.

For grids with ground rods in the corners, as well as along the perimeter and throughout the grid, the effective buried length, L_M , is

$$L_M = L_C + \left[1.55 + 1.22 \left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}} \right) \right] L_R \quad (11.27)$$

where L_r = length of each ground rod, m.

11.3.1.2 Step Voltage (E_s)

The maximum step voltage is assumed to occur over a distance of 1 m, beginning at and extending outside of the perimeter conductor at the angle bisecting the most extreme corner of the grid. The step voltage values are obtained as a product of the soil resistivity (ρ), the geometrical factor K_s , the corrective factor K_i , and the average current per unit of buried length of grounding system conductor (I_G/L_s):

$$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_s} \quad (11.28)$$

For the usual burial depth of $0.25 \text{ m} < h < 2.5 \text{ m}$ [2], K_s is defined as

$$K_s = \frac{1}{\pi} \left[\frac{1}{2 \cdot h} + \frac{1}{D + h} + \frac{1}{D} (1 - 0.5^{n-2}) \right] \quad (11.29)$$

and K_i as defined in Equation 11.25.

For grids with or without ground rods, the effective buried conductor length, L_s , is defined as

$$L_s = 0.75 \cdot L_C + 0.85 \cdot L_R \quad (11.30)$$

11.3.1.3 Evaluation of the Actual Touch- and Step-Voltage Equations

It is essential to determine the soil resistivity and maximum grid currents to design a substation grounding system. The touch and step voltages are directly proportional to these values. Overly conservative values of soil resistivity and grid current will increase the cost dramatically. Underestimating them may cause the design to be unsafe.

11.3.2 Soil Resistivity

Soil resistivity investigations are necessary to determine the soil structure. There are a number of tables in the literature showing the ranges of resistivity based on soil types (clay, loam, sand, shale, etc.) [9–11]. These tables give only very rough estimates. The soil resistivity can change dramatically with changes in moisture, temperature, and chemical content. To determine the soil resistivity of a particular site, soil resistivity measurements need to be taken. Soil resistivity can vary both horizontally and vertically, making it necessary to take more than one set of measurements. A number of measuring techniques are described in detail in IEEE Std. 81-1983, Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potential of a Ground System [12]. The most widely used test for determining soil resistivity data was developed by Wenner and is called either the Wenner or four-pin method. Using four pins or electrodes driven into the earth along a straight line at equal distances of a , to a depth of b , current is passed through the outer pins while a voltage reading is taken with the two inside pins. Based on the resistance, R , as determined by the voltage and current, the apparent resistivity can be calculated using the following equation, assuming b is small compared with a :

$$\rho_a = 2\pi a R \quad (11.31)$$

where it is assumed the apparent resistivity, ρ_a , at depth a is given by the equation.

Interpretation of the apparent soil resistivity based on field measurements is difficult. Uniform and two-layer soil models are the most commonly used soil resistivity models. The objective of the soil model is to provide a good approximation of the actual soil conditions. Interpretation can be done either manually or by the use of computer analysis. There are commercially available computer programs that take the soil data and mathematically calculate the soil resistivity and give a confidence level based on the test. Sunde developed a graphical method to interpret the test results.

The equations in IEEE Std. 80 require a uniform soil resistivity. Engineering judgment is required to interpret the soil resistivity measurements to determine the value of the soil resistivity, ρ , to use in the equations. IEEE Std. 80 presents equations to calculate the apparent soil resistivity based on field measurements as well as examples of Sunde's graphical method. Although the equations and graphical method are estimates, they provide the engineer with guidelines of the uniform soil resistivity to use in the ground grid design.

11.3.3 Grid Resistance

The grid resistance, i.e., the resistance of the ground grid to remote earth without other metallic conductors connected, can be calculated based on the following Sverak [2] equation:

$$R_g = \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right] \quad (11.32)$$

where

R_g = substation ground resistance, Ω

ρ = soil resistivity, Ω -m

A = area occupied by the ground grid, m^2

h = depth of the grid, m

L_T = total buried length of conductors, m

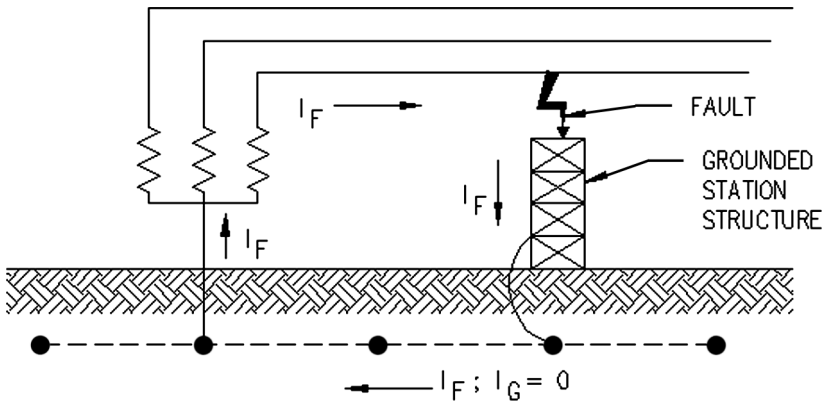


FIGURE 11.8 Fault within local substation; local neutral grounded.

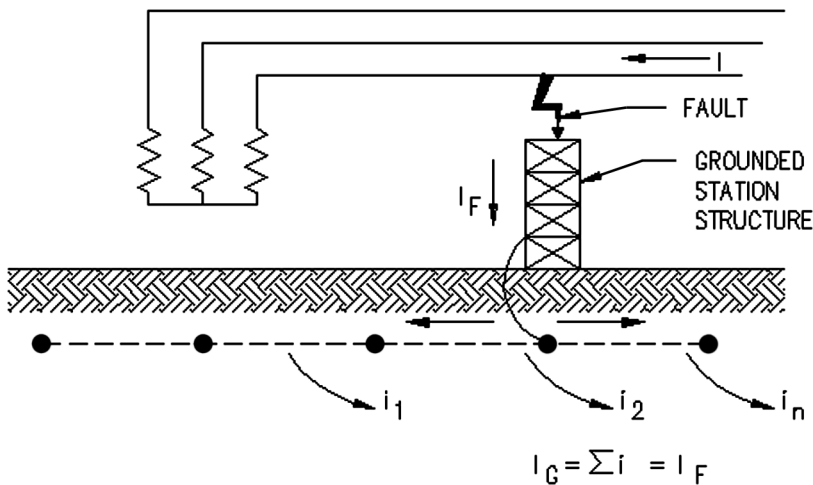


FIGURE 11.9 Fault within local substation; neutral grounded at remote location.

11.3.4 Grid Current

The maximum grid current must be determined, since it is this current that will produce the greatest ground potential rise (GPR) and the largest local surface potential gradients in and around the substation area. It is the flow of the current from the ground grid system to remote earth that determines the GPR.

There are many types of faults that can occur on an electrical system. Therefore, it is difficult to determine what condition will produce the maximum fault current. In practice, single-line-to-ground and line-to-line-to-ground faults will produce the maximum grid current. Figure 11.8 through Figure 11.11 show the maximum grid current, I_G , for various fault locations and system configurations.

Overhead ground wires, neutral conductors, and directly buried pipes and cables conduct a portion of the ground fault current away from the substation ground grid and need to be considered when determining the maximum grid current. The effect of these other current paths in parallel with the ground grid is difficult to determine because of the complexities and uncertainties in the current flow. Computer programs are available to determine the split between the various current paths. There are many papers available to determine the effective impedance of a static wire as seen from the fault point.

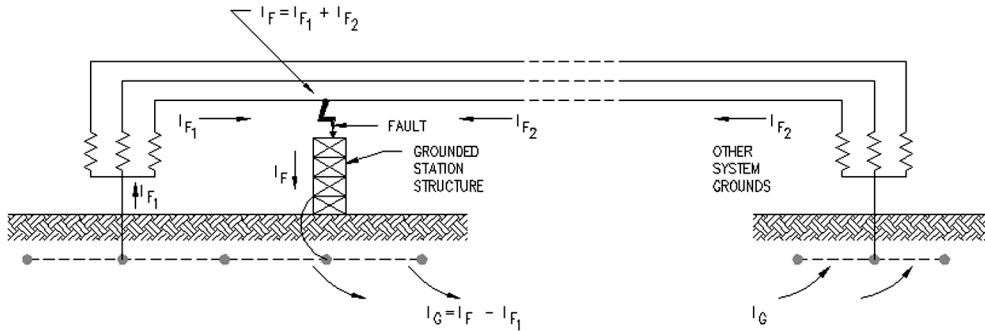


FIGURE 11.10 Fault in substation; system grounded at local station and also at other points.

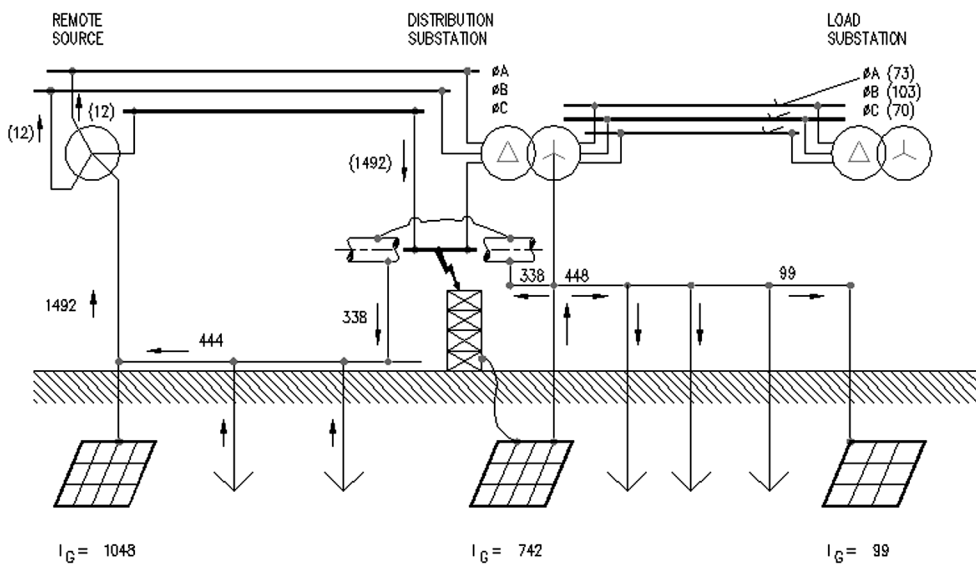


FIGURE 11.11 Typical current division for a fault on high side of distribution substation.

The fault current division factor, or split factor, represents the inverse of a ratio of the symmetrical fault current to that portion of the current that flows between the grounding grid and the surrounding earth.

$$S_f = \frac{I_g}{3I_o} \quad (11.33)$$

where

S_f = fault current division factor

I_g = rms symmetrical grid current, A

I_o = zero-sequence fault current, A

The process of computing the split factor, S_f , consists of deriving an equivalent representation of the overhead ground wires, neutrals, etc., connected to the grid and then solving the equivalent to determine what fraction of the total fault current flows between the grid and earth, and what fraction flows through the ground wires or neutrals. S_f is dependent on many parameters, some of which are:

1. Location of the fault
2. Magnitude of substation ground grid resistance
3. Buried pipes and cables in the vicinity of or directly connected to the substation ground system
4. Overhead ground wires, neutrals, or other ground return paths

Because of S_f , the symmetrical grid current I_g and maximum grid current I_G are closely related to the location of the fault. If the additional ground paths of items 3 and 4 above are neglected, the current division ratio (based on remote vs. local current contributions) can be computed using traditional symmetrical components. However, the current I_g computed using such a method may be overly pessimistic, even if the future system expansion is taken into consideration.

IEEE Std. 80 presents a series of curves based on computer simulations for various values of ground grid resistance and system conditions to determine the grid current. These split-current curves can be used to determine the maximum grid current. Using the maximum grid current instead of the maximum fault current will reduce the overall cost of the ground grid system.

11.3.5 Use of the Design Equations

The design equations above are limited to a uniform soil resistivity, equal grid spacing, specific buried depths, and relatively simple geometric layouts of the grid system. It may be necessary to use more sophisticated computer techniques to design a substation ground grid system for nonuniform soils or complex geometric layouts. Commercially available computer programs can be used to optimize the layout and provide for unequal grid spacing and maximum grid current based on the actual system configuration, including overhead wires, neutral conductors, underground facilities, etc. Computer programs can also handle special problems associated with fences, interconnected substation grounding systems at power plants, customer substations, and other unique situations.

11.3.6 Selection of Conductors

11.3.6.1 Materials

Each element of the grounding system, including grid conductors, connections, connecting leads, and all primary electrodes, should be designed so that for the expected design life of the installation, the element will:

- Have sufficient conductivity, so that it will not contribute substantially to local voltage differences
- Resist fusing and mechanical deterioration under the most adverse combination of a fault current magnitude and duration
- Be mechanically reliable and rugged to a high degree
- Be able to maintain its function even when exposed to corrosion or physical abuse

Copper is a common material used for grounding. Copper conductors, in addition to their high conductivity, have the advantage of being resistant to most underground corrosion because copper is cathodic with respect to most other metals that are likely to be buried in the vicinity. Copper-clad steel is usually used for underground rods and occasionally for grid conductors, especially where theft is a problem. Use of copper, or to a lesser degree copper-clad steel, therefore assures that the integrity of an underground network will be maintained for years, so long as the conductors are of an adequate size and not damaged and the soil conditions are not corrosive to the material used. Aluminum is used for ground grids less frequently. Though at first glance the use of aluminum would be a natural choice for GIS equipment with enclosures made of aluminum or aluminum alloys, there are several disadvantages to consider:

- Aluminum can corrode in certain soils. The layer of corroded aluminum material is nonconductive for all practical grounding purposes.
- Gradual corrosion caused by alternating currents can also be a problem under certain conditions.

Thus, aluminum should be used only after full investigation of all circumstances, despite the fact that, like steel, it would alleviate the problem of contributing to the corrosion of other buried objects. However, it is anodic to many other metals, including steel and, if interconnected to one of these metals in the presence of an electrolyte, the aluminum will sacrifice itself to protect the other metal. If aluminum is used, the high-purity electric-conductor grades are recommended as being more suitable than most alloys. Steel can be used for ground grid conductors and rods. Of course, such a design requires that attention be paid to the corrosion of the steel. Use of a galvanized or corrosion-resistant steel, in combination with cathodic protection, is typical for steel grounding systems.

A grid of copper or copper-clad steel forms a galvanic cell with buried steel structures, pipes, and any of the lead-based alloys that might be present in cable sheaths. This galvanic cell can hasten corrosion of the latter. Tinning the copper has been tried by some utilities because tinning reduces the cell potential with respect to steel and zinc by about 50% and practically eliminates this potential with respect to lead (tin being slightly sacrificial to lead). The disadvantage of using tinned copper conductor is that it accelerates and concentrates the natural corrosion, caused by the chemicals in the soil, of the copper in any small bare area. Other often-used methods are:

- Insulation of the sacrificial metal surfaces with a coating such as plastic tape, asphalt compound, or both.
- Routing of buried metal elements so that any copper-based conductor will cross water pipe lines or similar objects made of other uncoated metals as nearly as possible at right angles, and then applying an insulated coating to one metal or the other where they are in proximity. The insulated coating is usually applied to the pipe.
- Cathodic protection using sacrificial anodes or impressed current systems.
- Use of nonmetallic pipes and conduit.

11.3.6.2 Conductor Sizing Factors

Conductor sizing factors include the symmetrical currents, asymmetrical currents, limitation of temperatures to values that will not cause harm to other equipment, mechanical reliability, exposure to corrosive environments, and future growth causing higher grounding-system currents. The following provides information concerning symmetrical and asymmetrical currents.

11.3.6.3 Symmetrical Currents

The short-time temperature rise in a ground conductor, or the required conductor size as a function of conductor current, can be obtained from Equations 11.34 and 11.35, which are taken from the derivation by Sverak [13]. These equations evaluate the ampacity of any conductor for which the material constants are known. Equations 11.34 and 11.35 are derived for symmetrical currents (with no dc offset).

$$I = A_{mm^2} \sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_c \alpha_r \rho_r} \right) \ln \left(\frac{K_o + T_m}{K_o + T_a} \right)} \quad (11.34)$$

where

I = rms current, kA

A_{mm^2} = conductor cross section, mm²

T_m = maximum allowable temperature, °C

T_a = ambient temperature, °C

T_r = reference temperature for material constants, °C

α_0 = thermal coefficient of resistivity at 0°C, 1/°C

α_r = thermal coefficient of resistivity at reference temperature T_r , 1/°C

ρ_r = resistivity of the ground conductor at reference temperature T_r , μΩ-cm

K_o = $1/\alpha_0$ or $(1/\alpha_r) - T_r$, °C

t_c = duration of current, sec

TCAP = thermal capacity per unit volume, J/(cm³·°C)

Note that α_r and ρ_r are both to be found at the same reference temperature of T_r degrees Celsius. If the conductor size is given in kcmils ($\text{mm}^2 \times 1.974 = \text{kcmils}$), Equation 11.34 becomes

$$I = 5.07 \cdot 10^{-3} A_{\text{kcmil}} \sqrt{\left(\frac{TCAP}{t_c \alpha_r \rho_r} \right) \ln \left(\frac{K_o + T_m}{K_o + T_a} \right)} \quad (11.35)$$

11.3.6.4 Asymmetrical Currents: Decrement Factor

In cases where accounting for a possible dc offset component in the fault current is desired, an equivalent value of the symmetrical current, I_F , representing the rms value of an asymmetrical current integrated over the entire fault duration, t_c , can be determined as a function of X/R by using the decrement factor D_f , Equation 11.35, prior to the application of Equation 11.34 and Equation 11.35.

$$I_F = I_f \cdot D_f \quad (11.36)$$

$$D_f = \sqrt{1 + \frac{T_a}{t_f} \left(1 - e^{\frac{-2t_f}{T_a}} \right)} \quad (11.37)$$

The resulting value of I_F is always larger than I_f because the decrement factor is based on a very conservative assumption that the ac component does not decay with time but remains constant at its initial subtransient value.

The decrement factor is dependent on both the system X/R ratio at the fault location for a given fault type and the duration of the fault. The decrement factor is larger for higher X/R ratios and shorter fault durations. The effects of the dc offset are negligible if the X/R ratio is less than five and the duration of the fault is greater than 1 sec.

11.3.7 Selection of Connections

All connections made in a grounding network above and below ground should be evaluated to meet the same general requirements of the conductor used, namely electrical conductivity, corrosion resistance, current-carrying capacity, and mechanical strength. These connections should be massive enough to maintain a temperature rise below that of the conductor and to withstand the effect of heating, be strong enough to withstand the mechanical forces caused by the electromagnetic forces of maximum expected fault currents, and be able to resist corrosion for the intended life of the installation.

IEEE Std. 837, Qualifying Permanent Connections Used in Substation Grounding [14], provides detailed information on the application and testing of permanent connections for use in substation grounding. Grounding connections that pass IEEE Std. 837 for a particular conductor size range and material should satisfy all the criteria outlined above for that same conductor size, range, and material.

11.3.8 Grounding of Substation Fence

Fence grounding is of major importance, since the fence is usually accessible to the general public, children and adults. The substation grounding system design should be such that the touch potential on the fence is within the calculated tolerable limit of touch potential. Step potential is usually not a concern at the fence perimeter, but this should be checked to verify that a problem does not exist. There are various ways to ground the substation fence. The fence can be within and attached to the ground grid, outside and attached to the ground grid, outside and not attached to the ground grid, or separately grounded such as through the fence post. IEEE Std. 80 provides a very detailed analysis of the different grounding situations. There are many safety considerations associated with the different fence-grounding options.

11.3.9 Other Design Considerations

There are other elements of substation grounding system design that have not been discussed here. These elements include the refinement of the design, effects of directly buried pipes and cables, special areas of concern including control- and power-cable grounding, surge arrester grounding, transferred potentials, and installation considerations.

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